2019 RHIC & AGS
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Future Heavy Flavor and Quarkonia Measurements from sPHENIX

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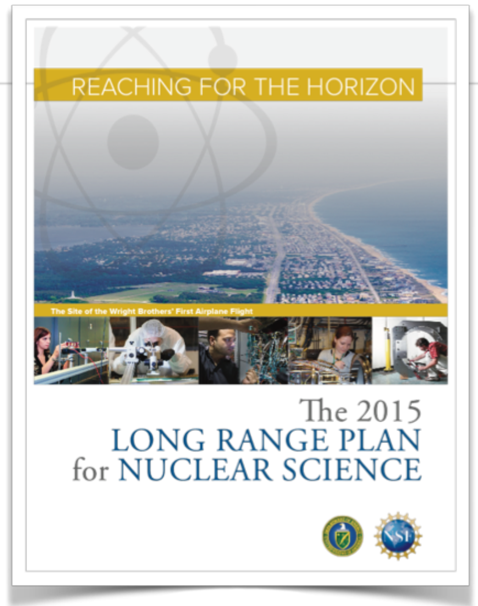
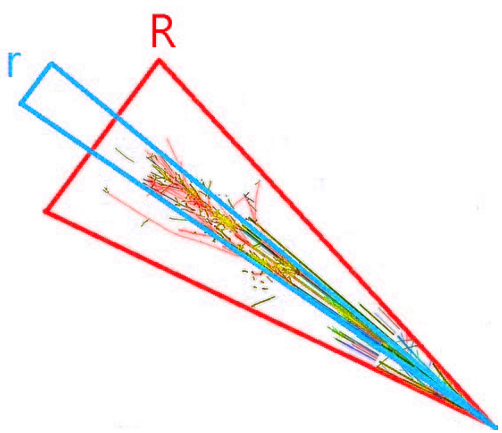
sPHENIX science mission

There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC.**

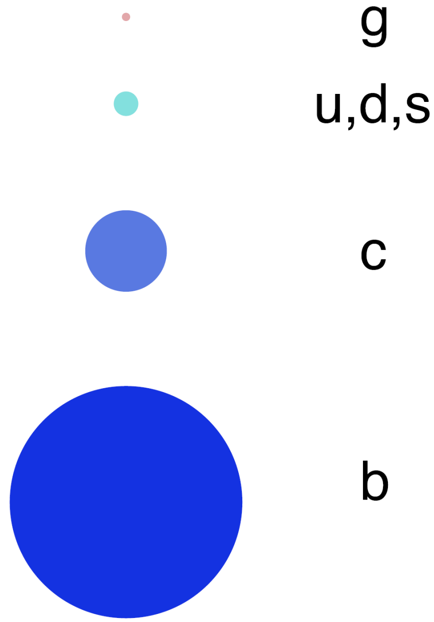


Core sPHENIX physics program

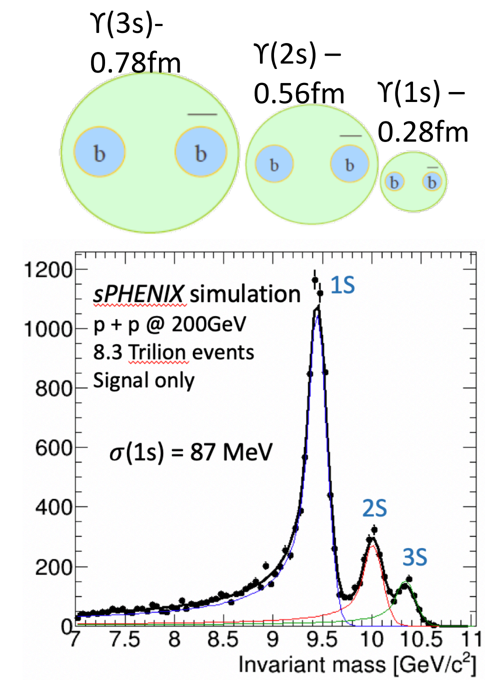
Jet cor. & substructure
Vary momentum/angular size of probe



Parton energy loss
Vary mass/momentum of probe

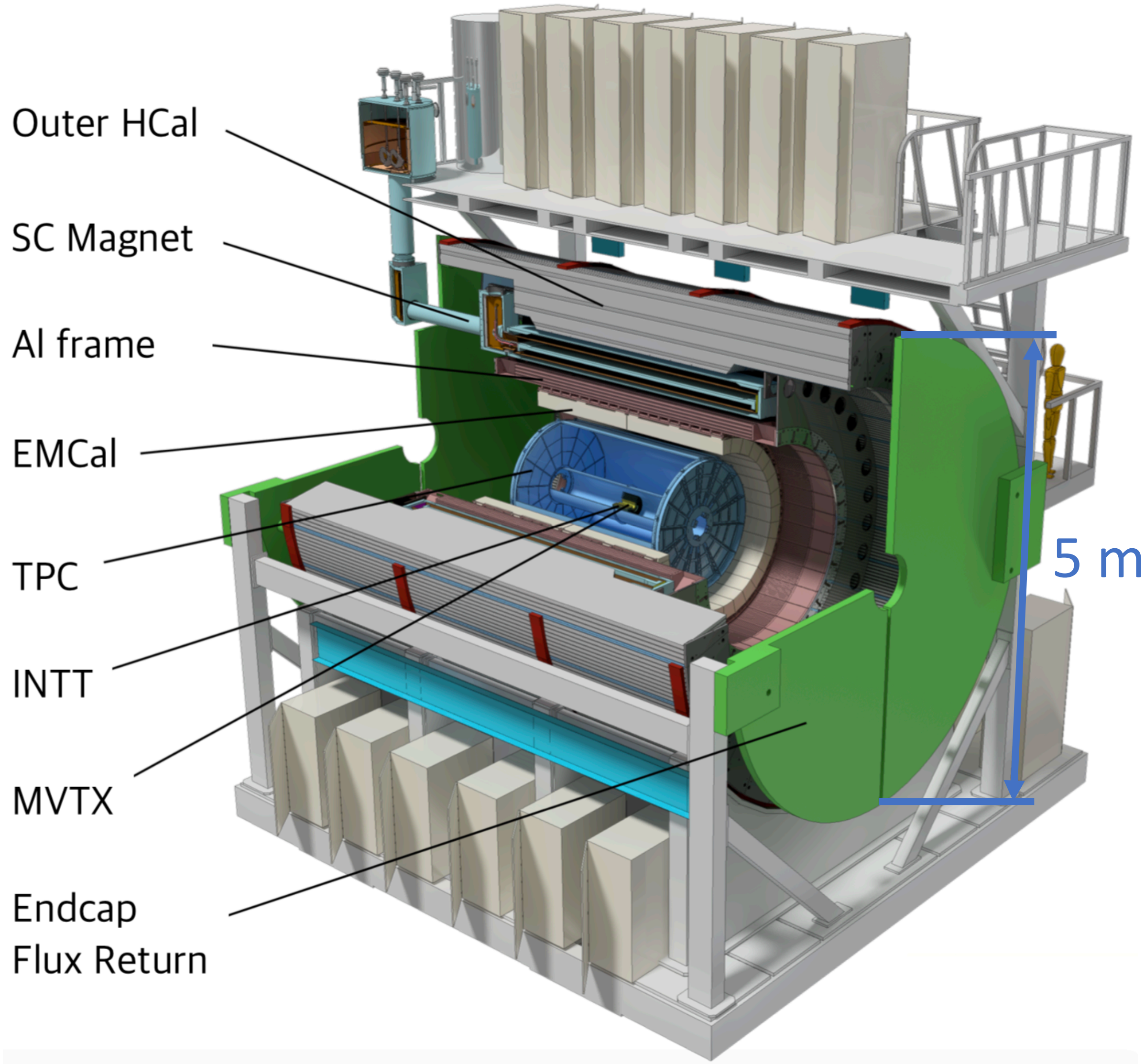


Upsilon spectroscopy
Vary size of the probe



This talk: Heavy flavor and quarkonia physics

sPHENIX detector



High luminosity
High rate

15 kHz trigger
>10 GB/s data

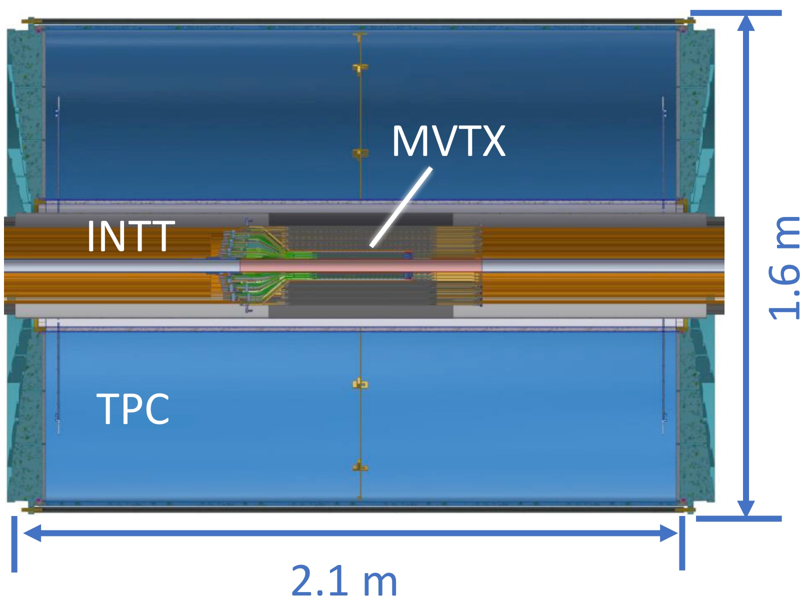
Full ϕ coverage

For |z|<10 cm:
|η|<1.1

sPHENIX tracking system

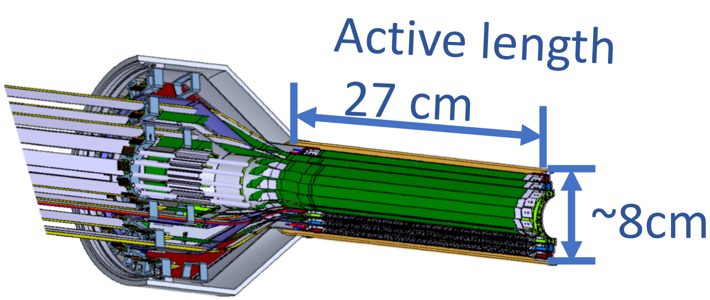
Outer tracker:

- **TPC** (20 cm < r < 78 cm) :
  - gateless and continuous readout
  - Provide momentum measurement

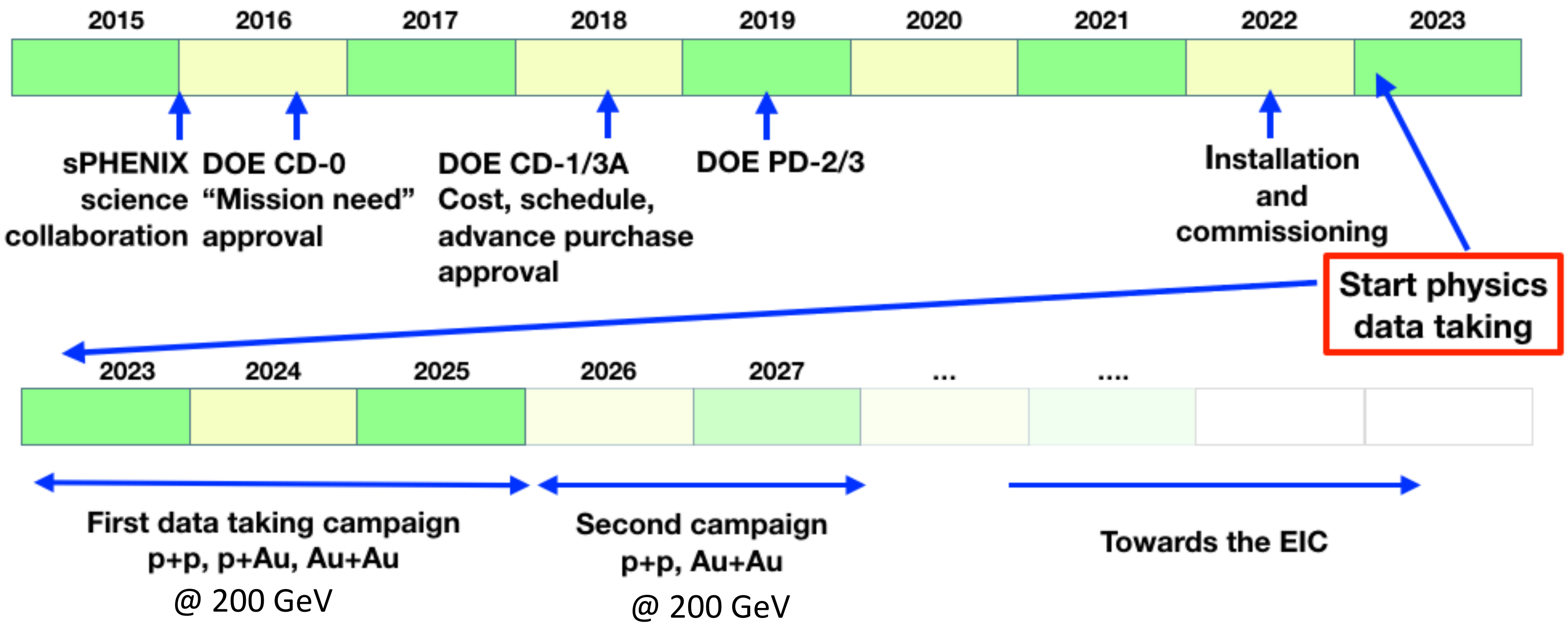


Inner tracker:

- **INTT** (6 cm < r < 12 cm) :
  - strip silicon sensors (2-layer)
  - Pattern recognition, timing
- **MVTX** (2.3 cm < r < 3.9 cm):
  - MAPS pixel sensors (3-layer)
  - Procurement copies of ALICE ITS IB staves integrated into sPHENIX
  - Precision vertexing



Timeline



Au+Au @ 200 GeV at 15 kHz for |z| < 10 cm:

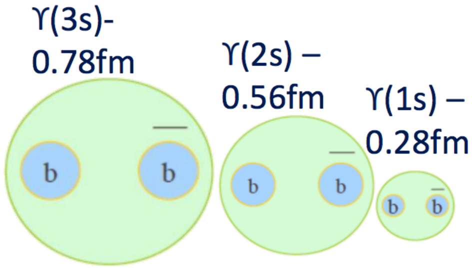
Total 239 billion events

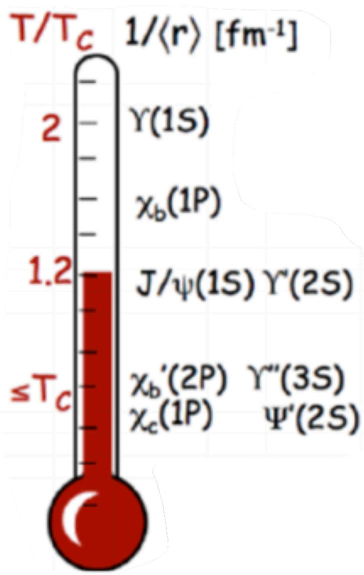
p + p @ 200 GeV at 15 kHz for |z| < 10 cm:

Total 8300 billion sampling events

High statistics!

Precision Upsilon spectroscopy





QGP "Thermometer"

A. Mocsy, EPJ C61, 705 (2009)

Quarkonium:

Color screening → dissociation

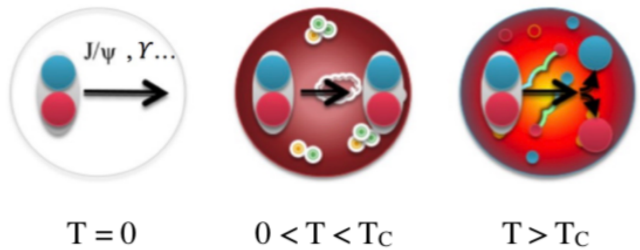


Illustration: A. Rothkopf

Different binding energy and radii of different states

→ "Sequential melting"

Why **Υ** @ RHIC ?

Regeneration is smaller compared to J/ψ;

Less effect from bottom coalescence;

Temperature dependence of Debye screening length.

Precision Upsilon

Challenge:

Small production cross section

~ $\bar{b}b$ pair 0.05/event

Goal :

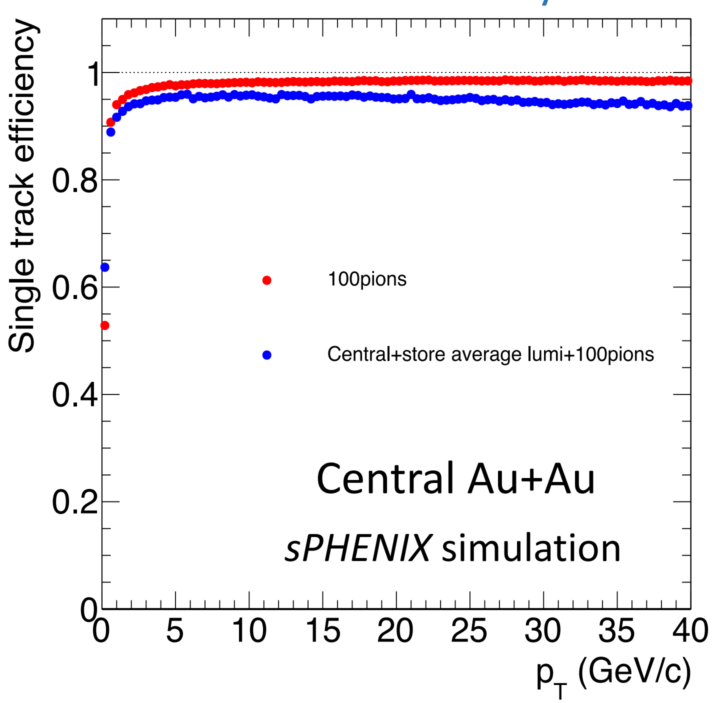
Separate $\Upsilon(1s)$ / $\Upsilon(2s)$/ $\Upsilon(3s)$

Requirement:

δM/M < 125 MeV

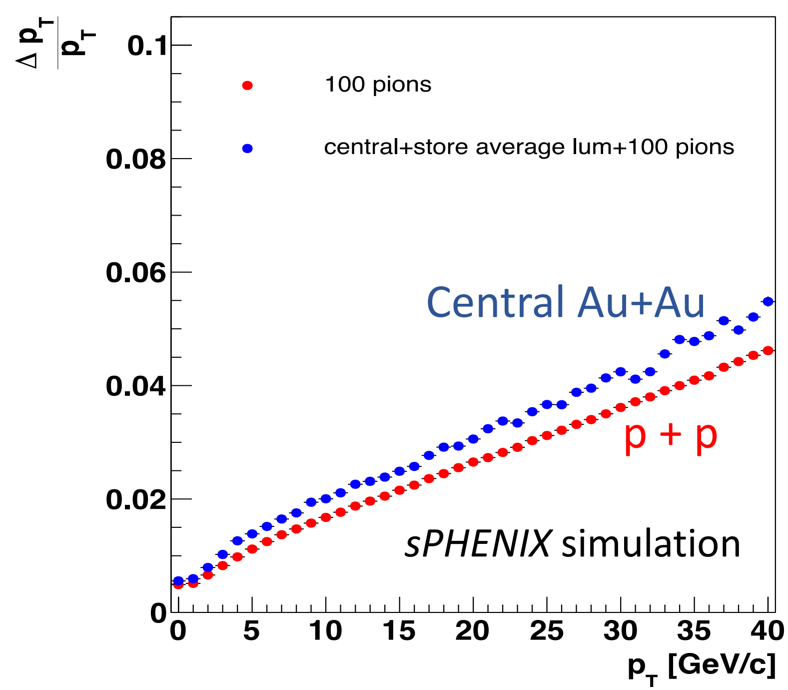
Tracking efficiency

> 90% efficiency



Momentum resolution

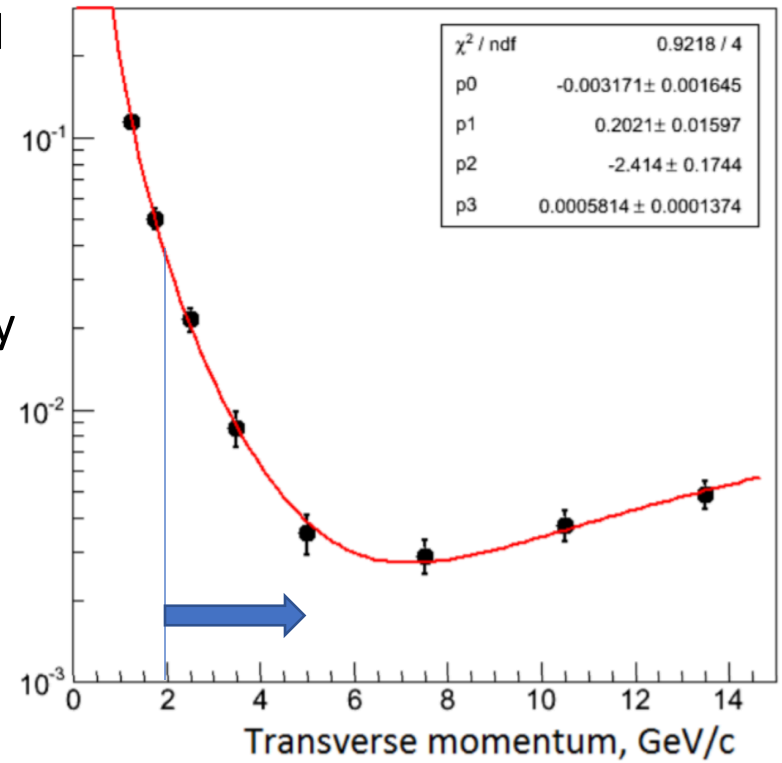
$\delta p/p < 2\%$ for $p_T<10$ GeV/c



Electron identification

- $\Upsilon(ns) \rightarrow ee$
- Use E_{CEMC}/p for eID
  - E_{CEMC} is the energy deposit in central EMC
- Hadron rejection factor is considered
  - $K/\pi/p/\bar{p}$
- 90% eID efficiency

Hadron rejection factor
= electron efficiency / hadron efficiency

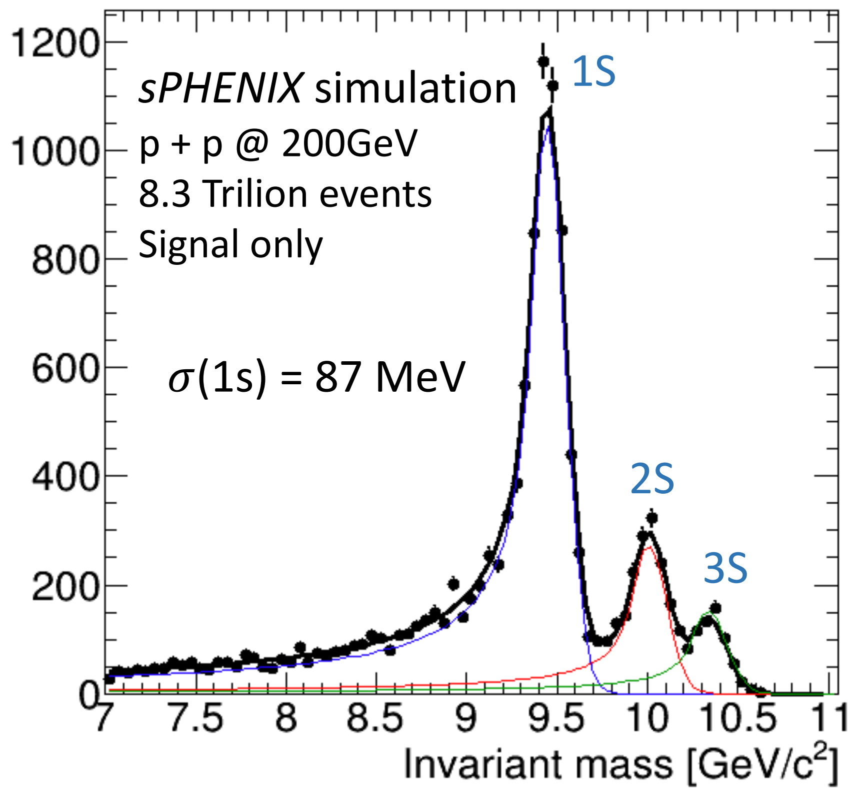


Inverse pion rejection factor

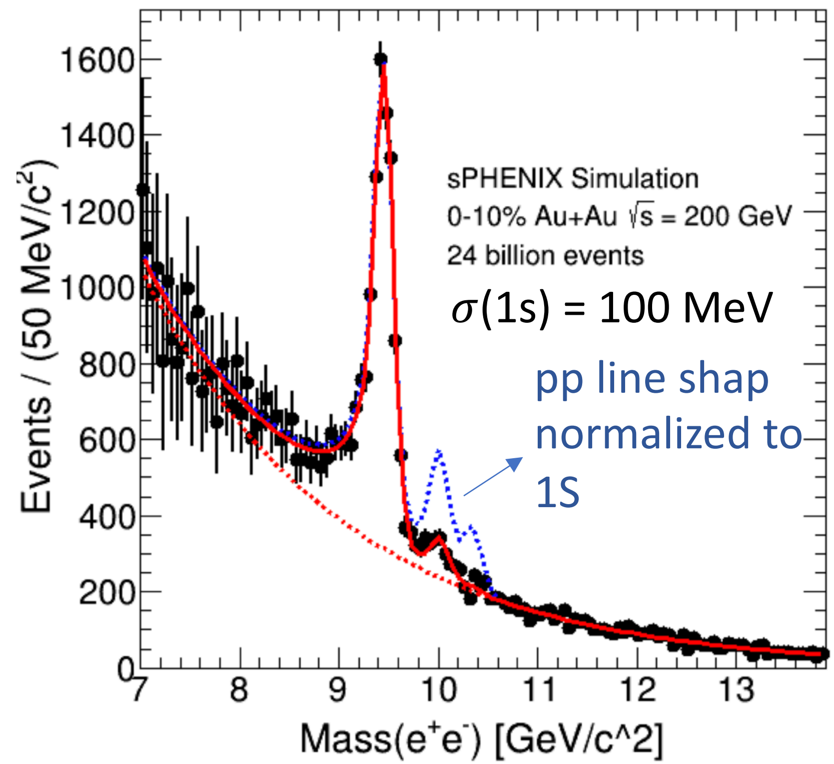
Upsilon signal projections

- sPHENIX provides excellent mass resolution.

$$\Upsilon(ns) \rightarrow ee$$



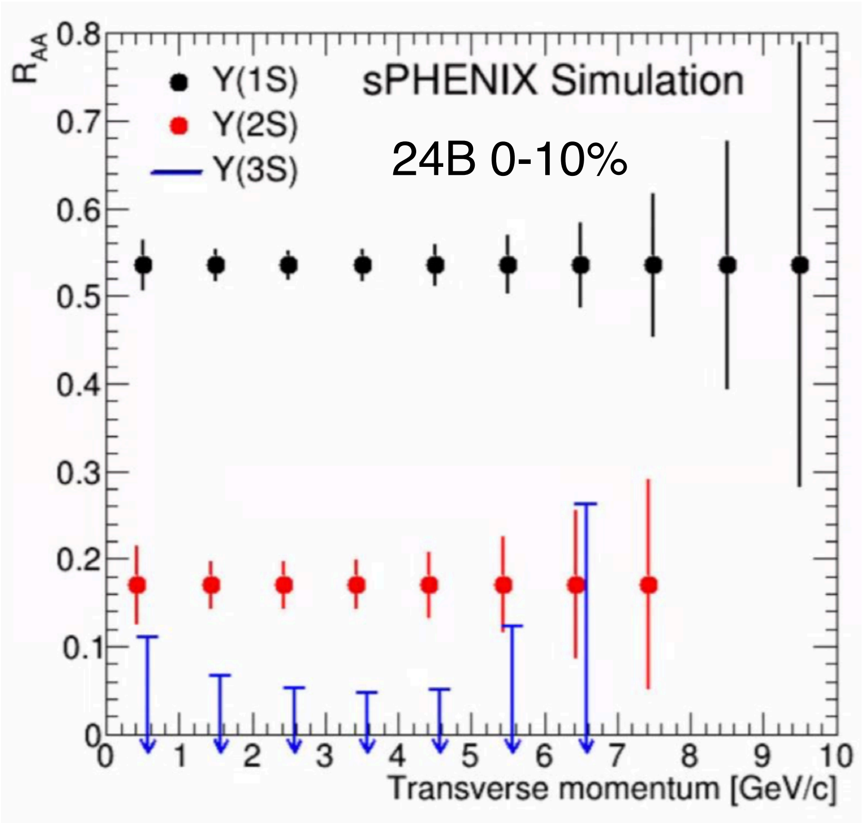
Integral Upsilon signal in p + p



Integral Upsilon signal in Au + Au

Upsilon R_{AA} projections

- Precise ϒ(1s) and ϒ(2s) R_{AA} measurement is expected at $0 < p_T < 8$ GeV.



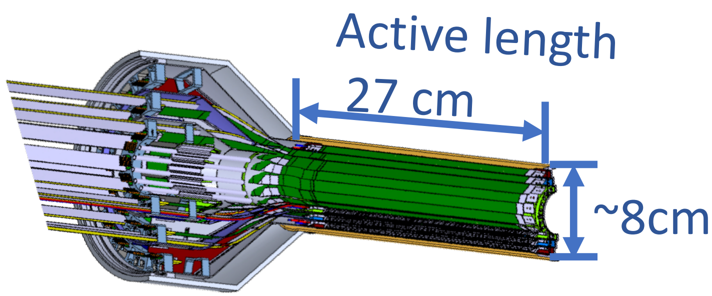
R_{AA} assumption: Nucl. Phys. A879 25, (2012)

MVTX: enable HF physics!

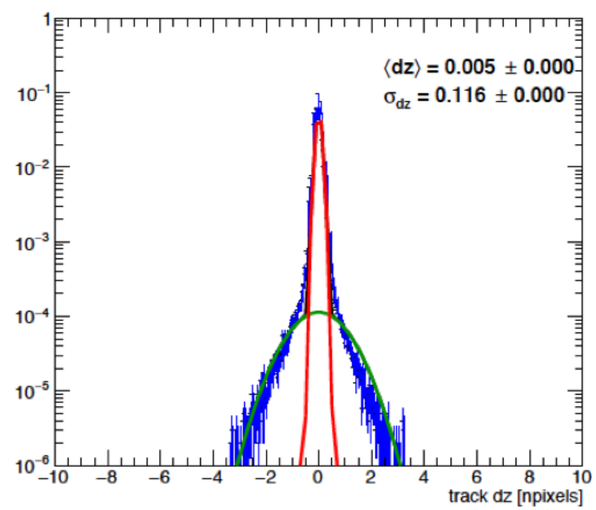
In close coordination with ALICE / ATLAS Phase-I upgrade

-Sensors:
ALICE ALPIDE sensors identical ITS/IB design
-Readout:
ALICE frontend Readout Unit(RU)
ATLAS upgrade backend FELIX boards
-Mechanics:
Modified mechanical frame design for sPHENIX

MVTX: 3-layer MAPS pixel sensors



Hit spatial resolution: < 5 μm

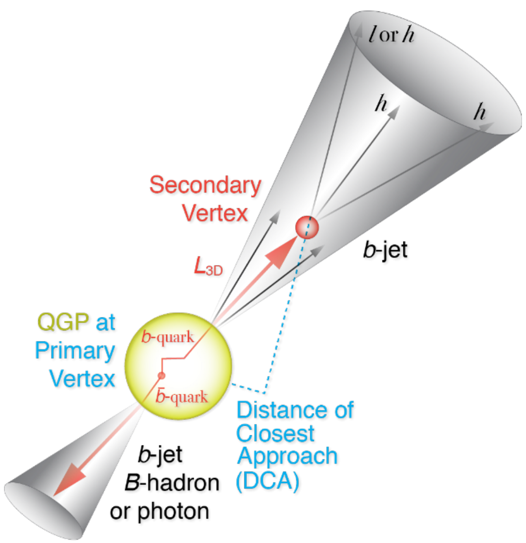


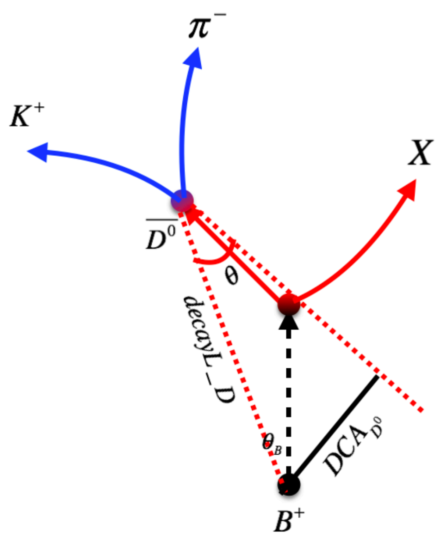
MVTX spatial resolution

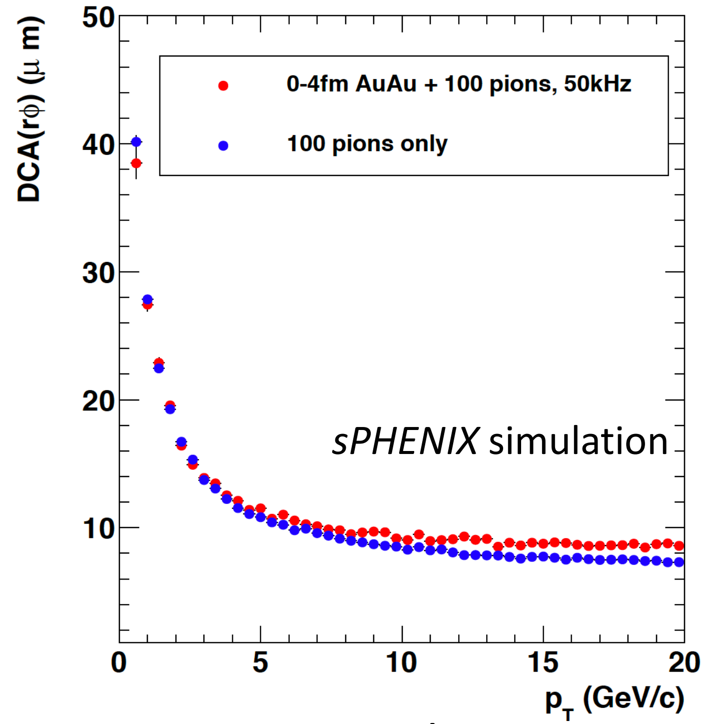
full chain **test beam** at FNAL @2018

Heavy flavor observables

- Precision vertex tracker + Good momentum resolution + High rate
  → Precision charm/bottom observables over wide scales
- *B*-meson @ 2< p_T <10 GeV/c, *b*-jet @ 15< p_T<35 GeV/c
- Goals: sPH-HF-2018-001 - MVTX Proposal
  - Diffusion of HF quark in QGP, differentiate collision and radiative energy loss, HF hadronization



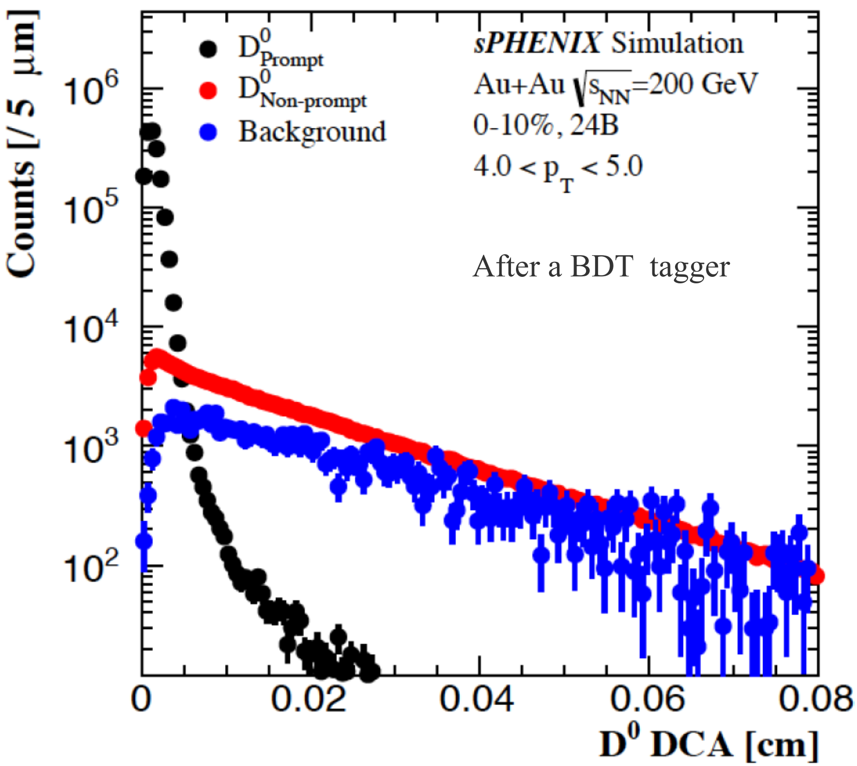




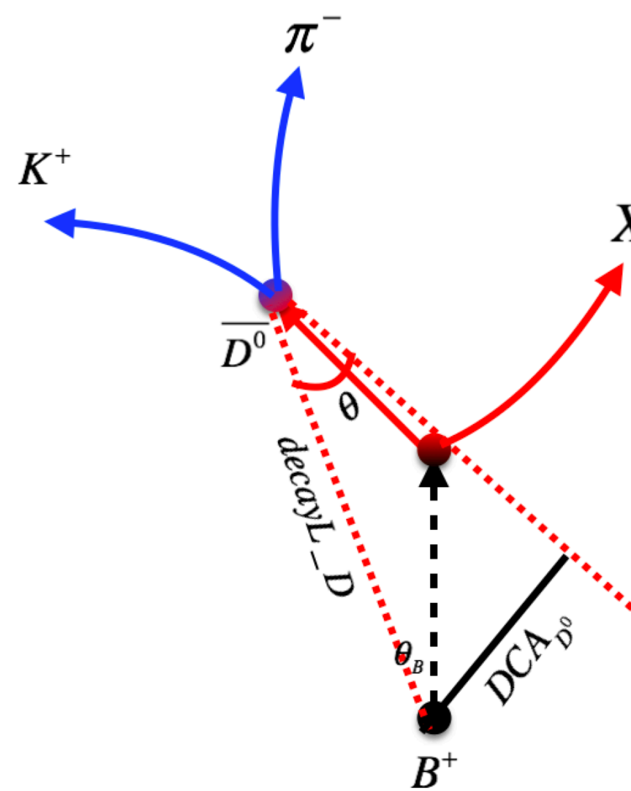
DCA resolution

Precise B→D measurement

- Explore B→D (non-prompt D meson) through D^0 DCA distribution



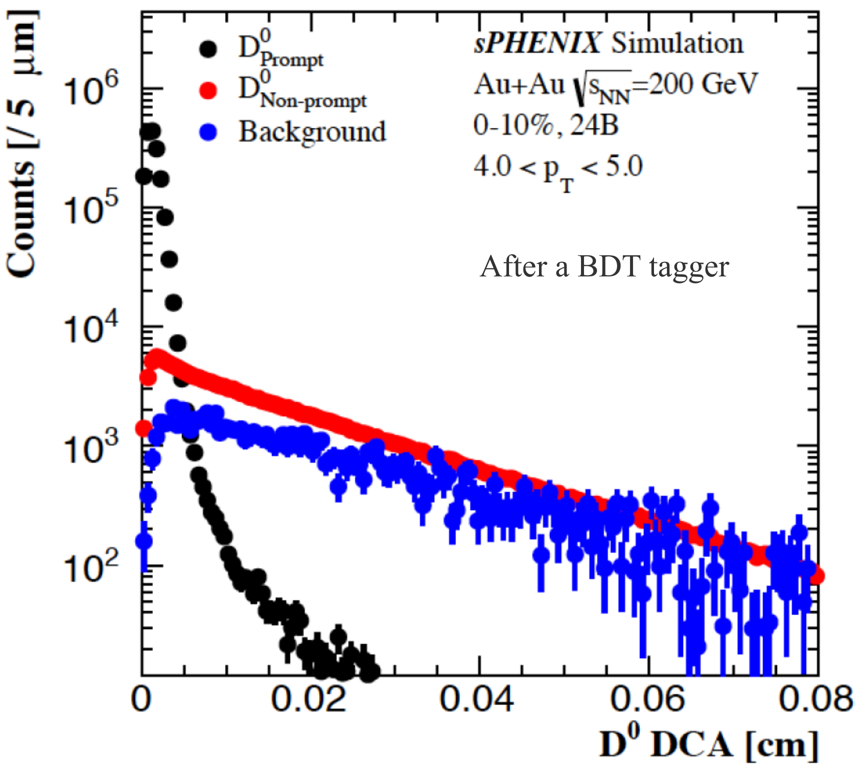
Prompt and non-prompt D-meson



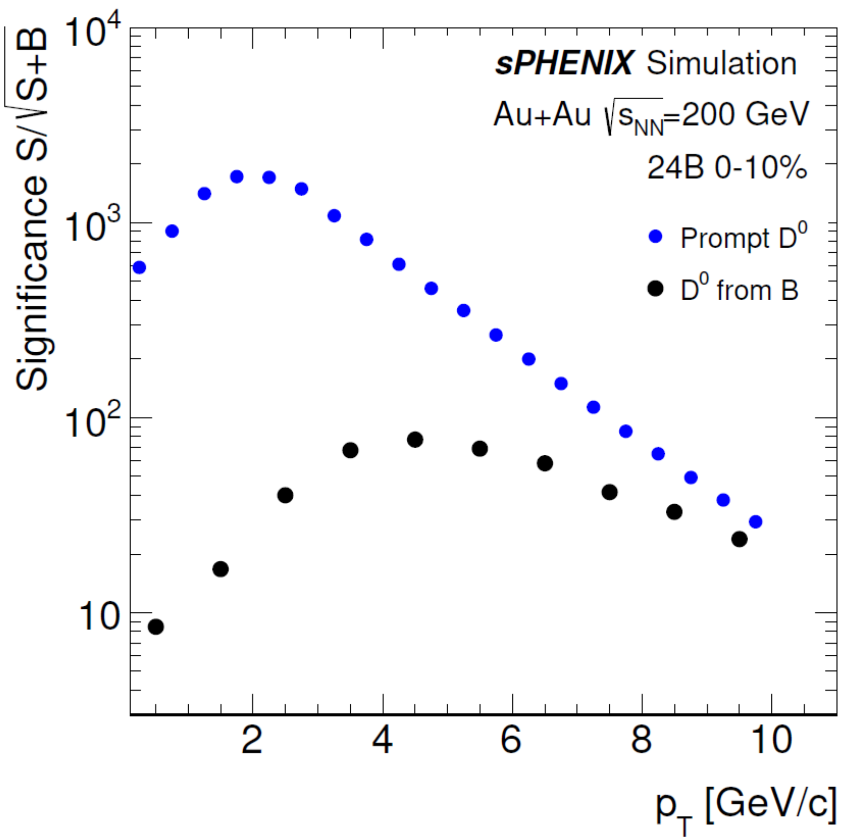
$$B \rightarrow \overline{D}^0 + X$$

Non-prompt D projections

- Explore B→D (non-prompt D meson) through D^0 DCA distribution
- High statistics and significance *B* meson via non-prompt D decay



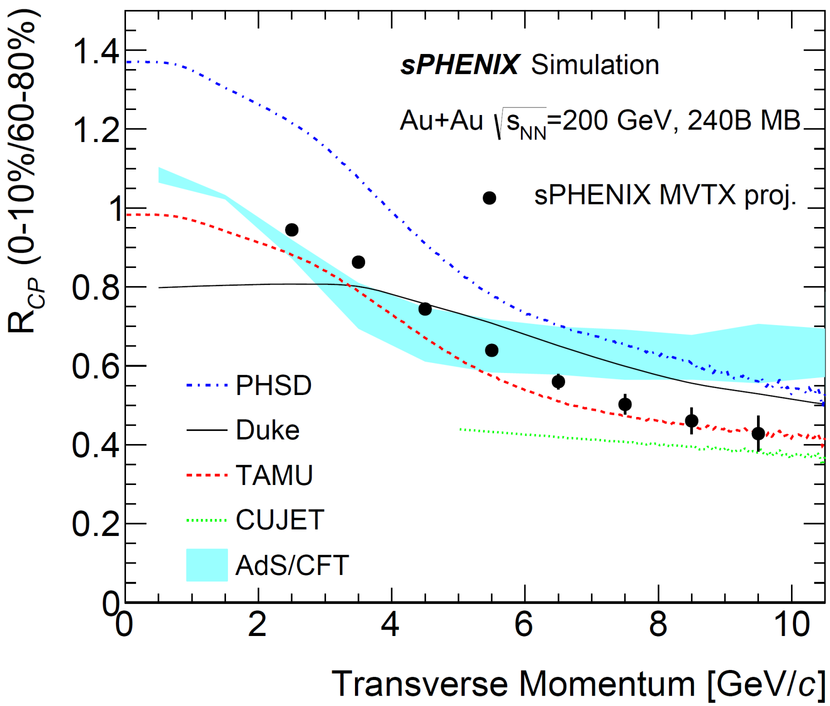
Prompt and non-prompt D-meson

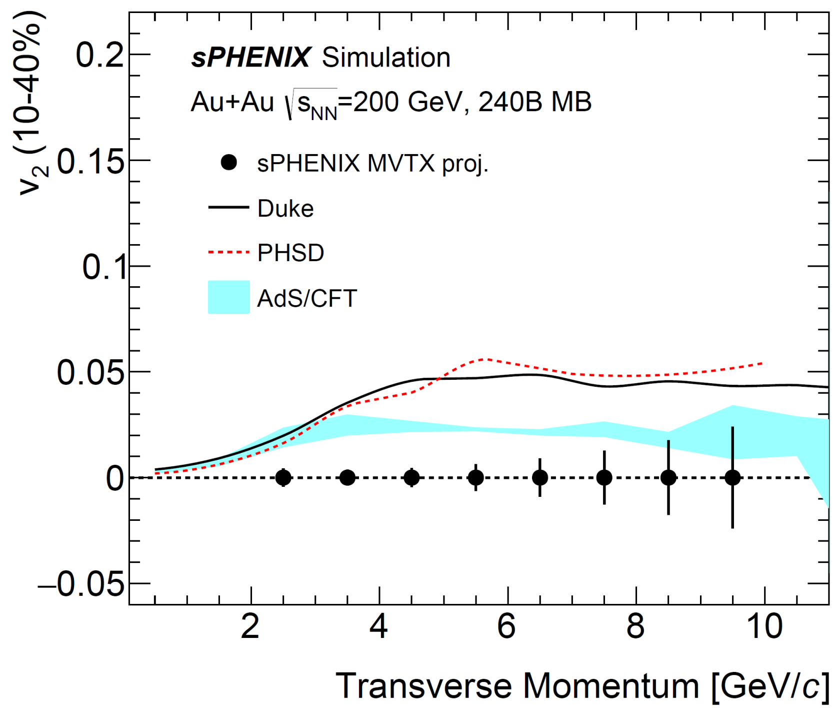


Non-prompt D projections

- High precision non-prompt-*D* suppression @ RHIC
  - Collisional and radiative energy loss
- Determine the bottom quark collectivity
  - clean access to D_{HQ} at RHIC energy

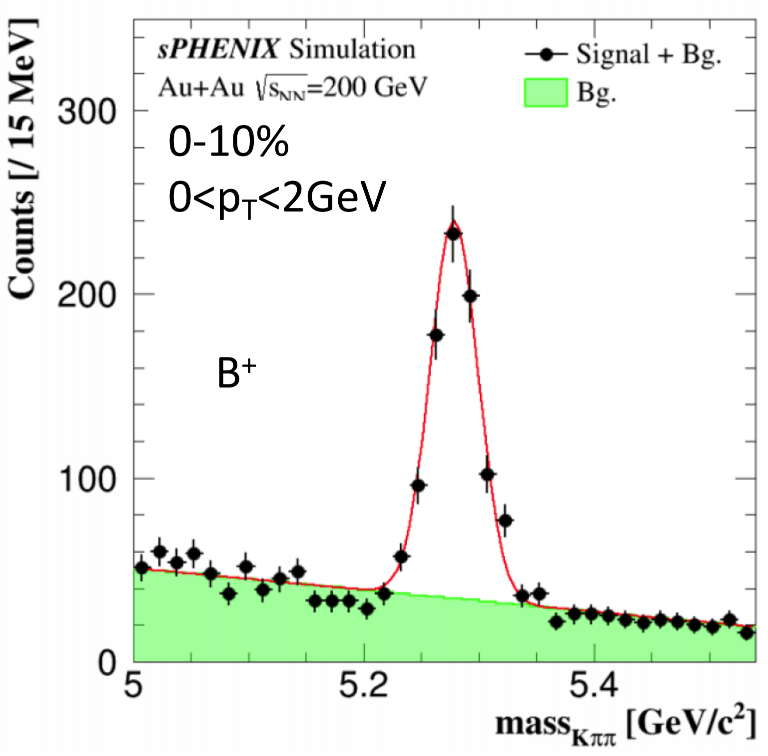
non-prompt *D*-meson and predictions for sPHENIX

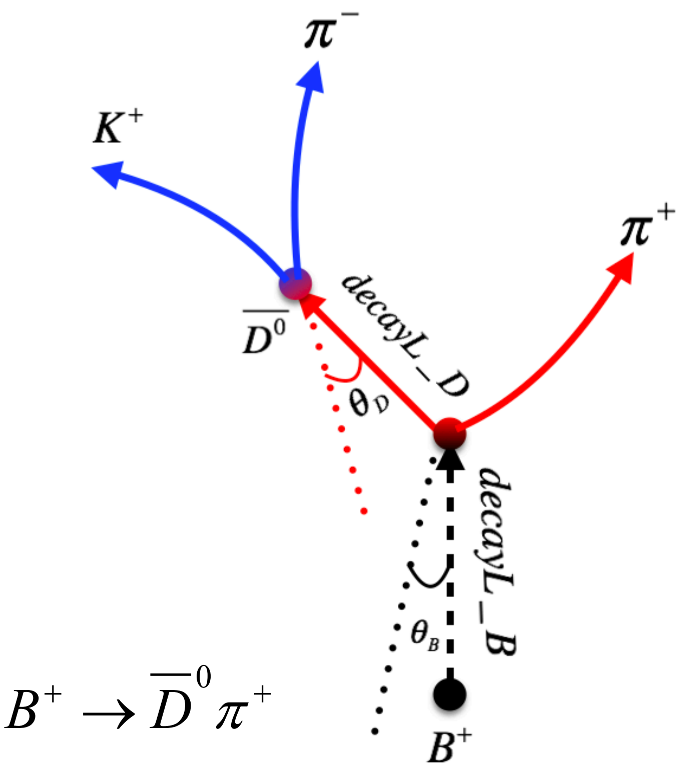




Precise B^+ measurement

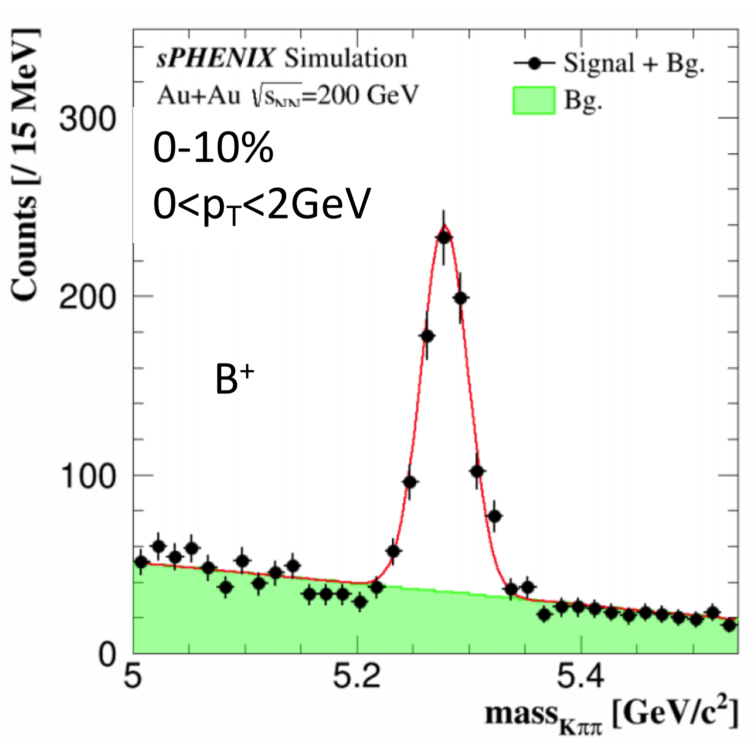
- Reconstruct B^+ through $B^+ \to \overline{D}^0 \pi^+$
- Beautiful signal event at $p_T < 2$ GeV

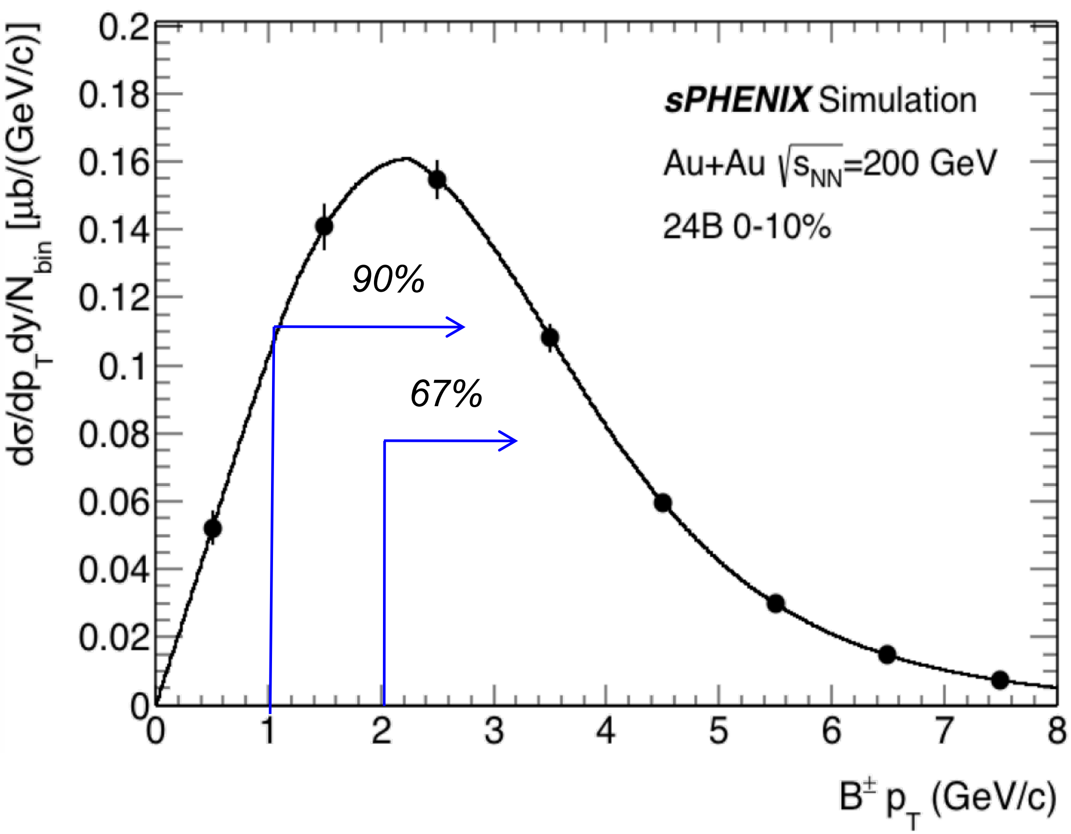




Precise B^+ measurement

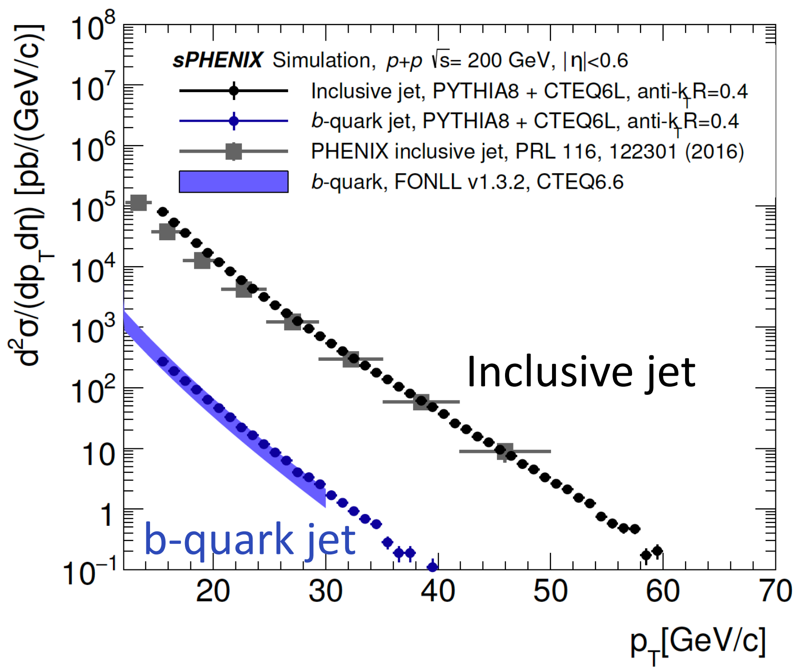
- Reeconstruct B^+ through $B^+ \rightarrow \overline{D}^0 \pi^+$
- Beautiful signal event at $p_T < 2$ GeV
- Precise B^+ spectra measurement is expected.



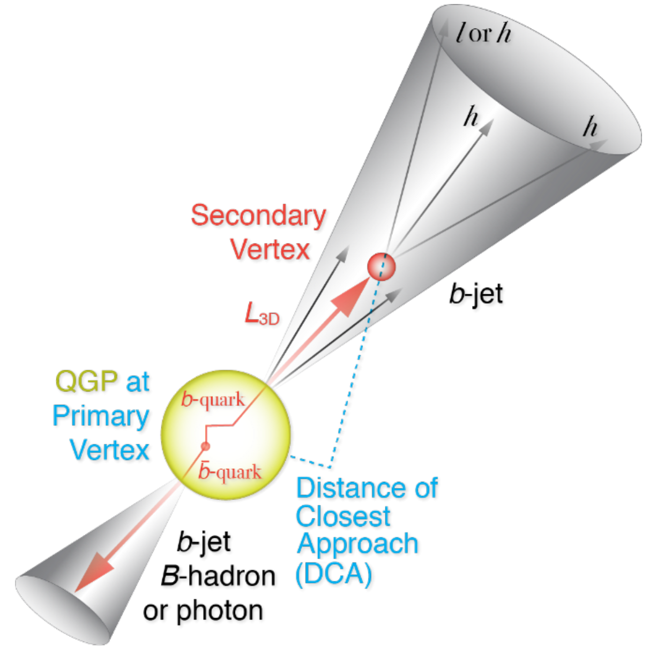


b-jet tagging @ sPHENIX

- sPHENIX is an excellent jet detector
- b-jet: very small cross section
- B-hadron decay topology:
    - decay length ~ few mm
    - decay to multi-particles.



p+p @ 200 GeV



Algorithms for b-jet tagging:

Tracking counting tagging:

Count No. of tracks > DCA cut

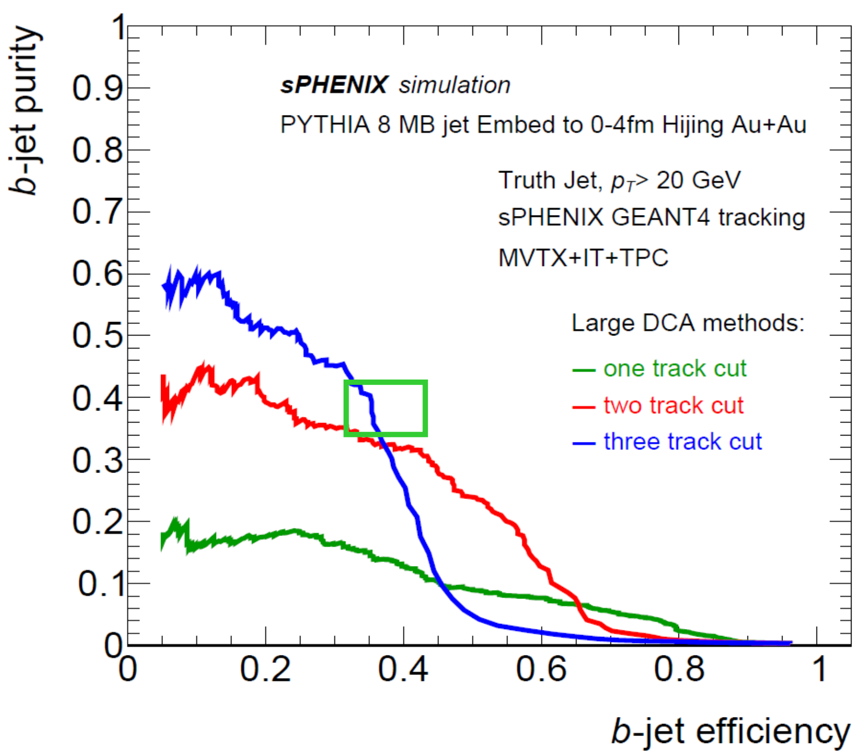
Secondary vertex tagging:

multiple tracks coming from the same secondary vertex.

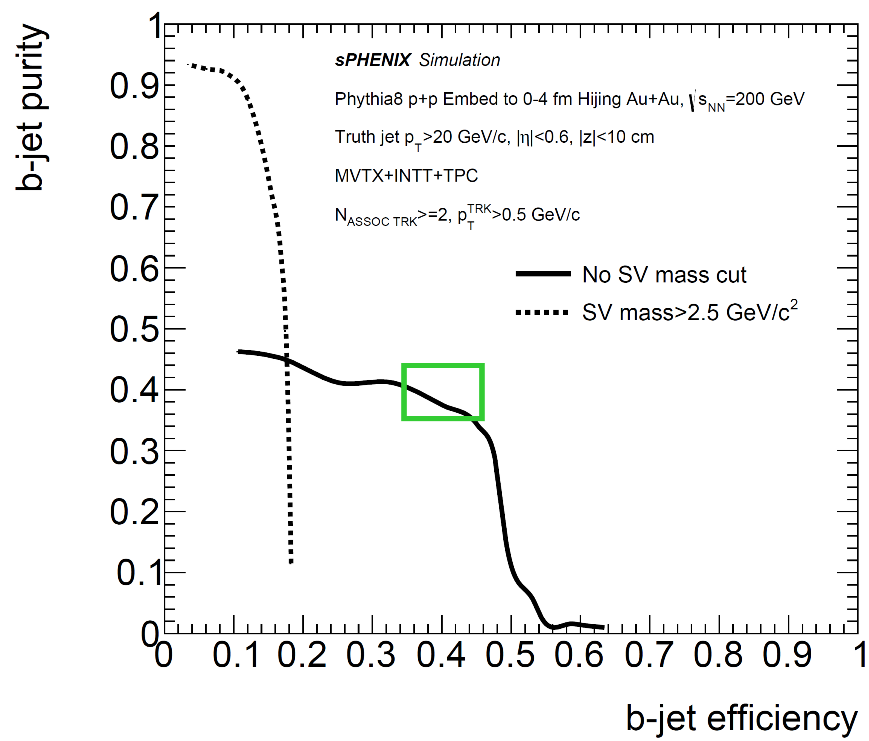
b-jet tagging @ sPHENIX

- Demonstrate b-jet capability: tagging algorithms evaluated using full detector HIJING simulation
- Reaching an optimal working point in central Au+Au collisions

Track-counting tagger



Secondary-vertex tagger

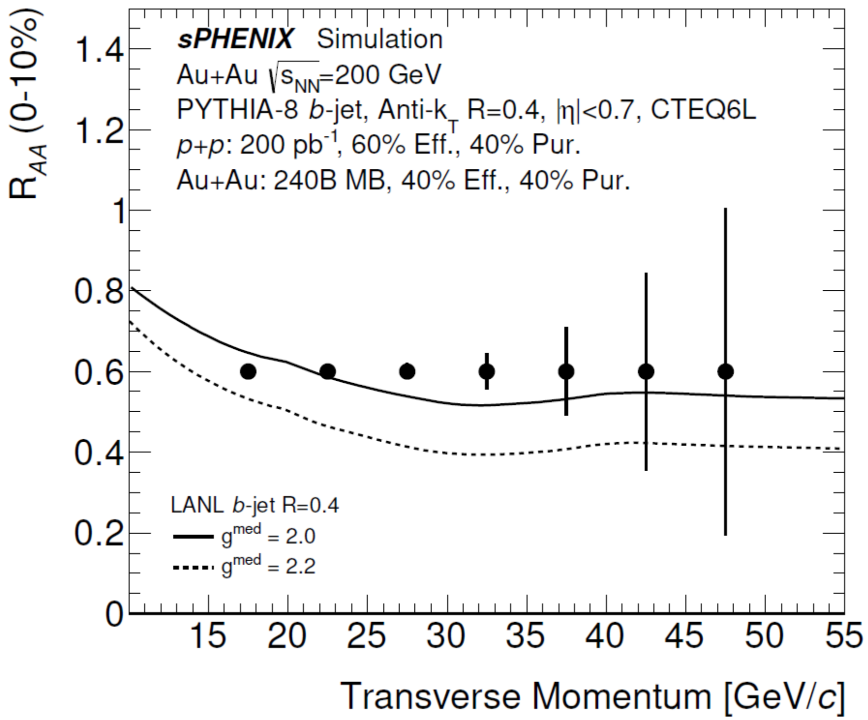


CMS work-point, Phys. Rev. Lett. 113, 132301 (2014)

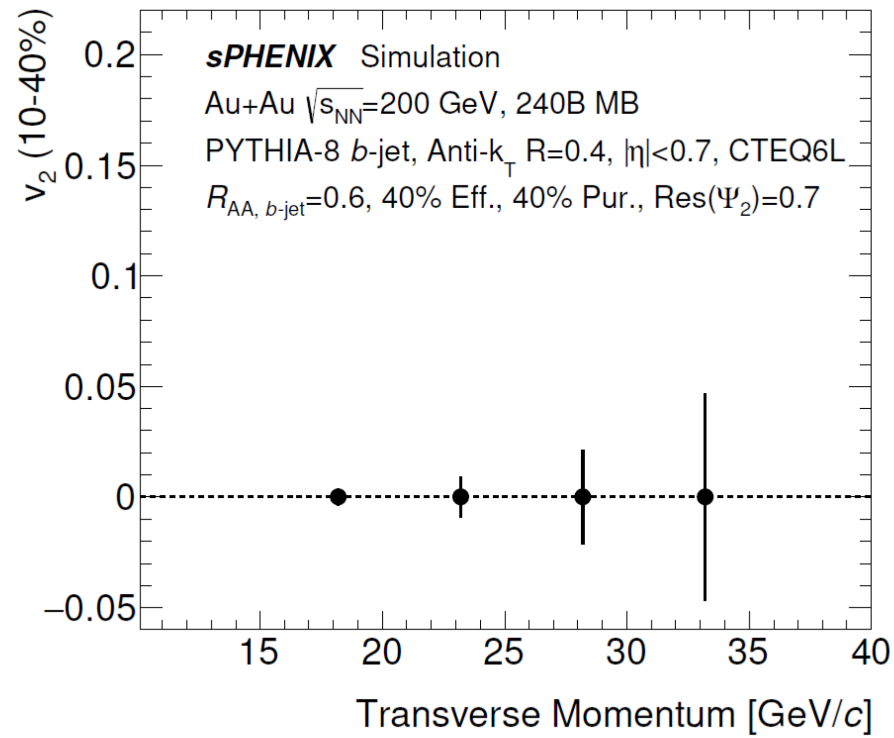
b-jet projection

- High precision inclusive *b*-jet suppression and v_2 measurement @ RHIC
- Strong constraints on energy loss model of high energy probe in QGP.

Inclusive b-jet R_{AA}



Inclusive b-jet v_2



Working point : p+p 60% purity 40% efficiency

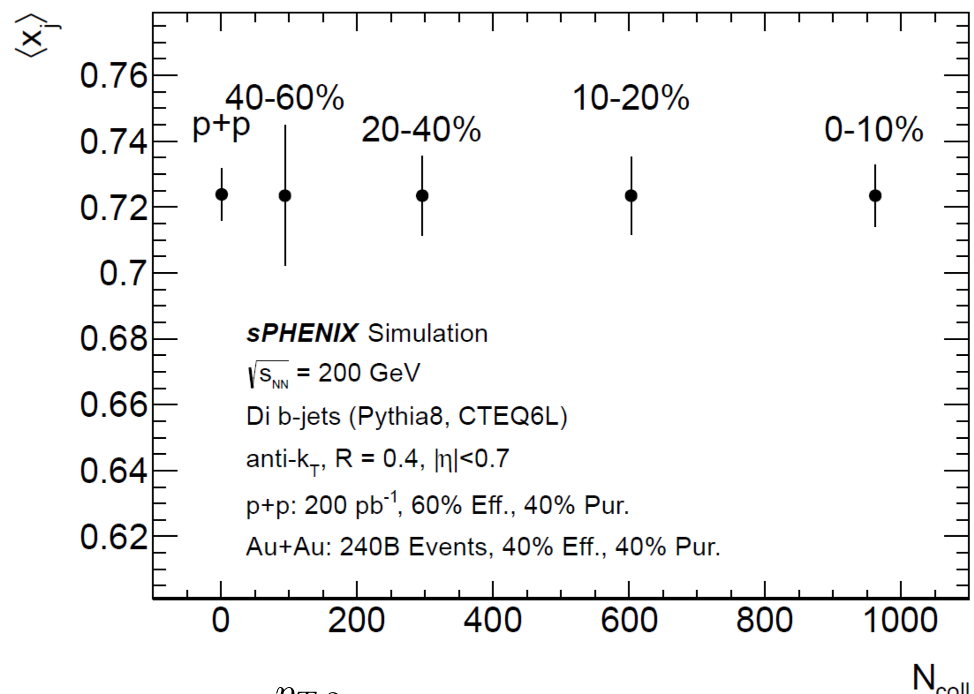
Au+Au 40% purity 40% efficiency

Broader topic:
Bottom observables

Opportunities for new ideas and new measurements!

- HF-jet-jet
- jet-HF-hadron
- D- $\overline{\mathrm{D}}$ correlations
- HF jet substructure
- Total *b*-cross section
- other B decay channels
  - B $\rightarrow J/\psi$ and more ?

…….

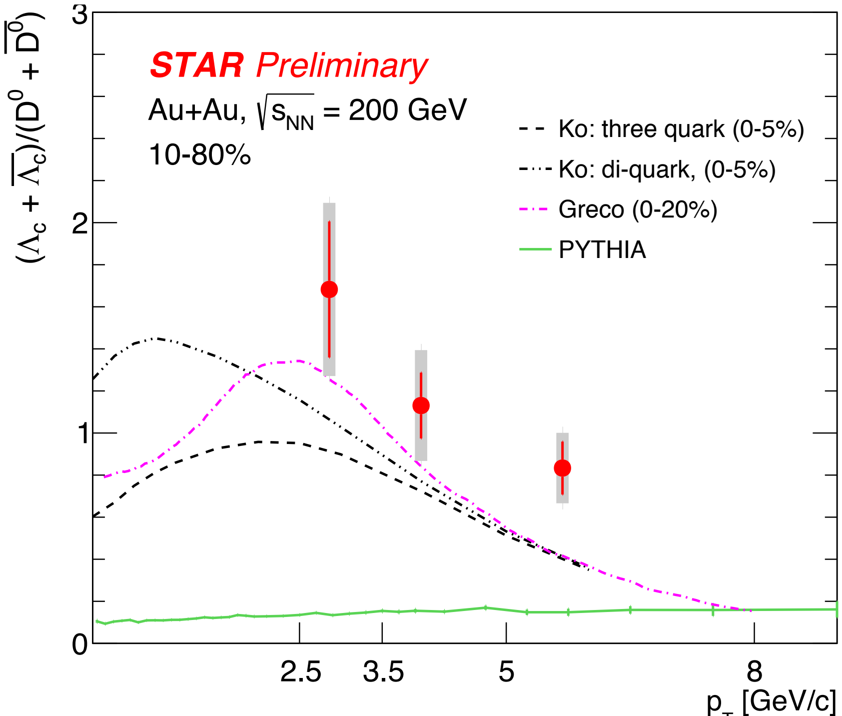


$$x_j = \frac{p_{T,2}}{p_{T,1}}$$

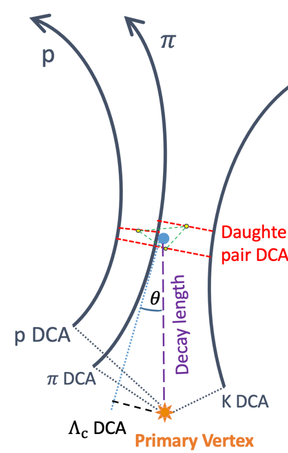
Di-b-jet p_T asymmetry

Λ_c production @ RHIC

- Heavy quark hadronization mechanism
- Strong enhancement of Λ_c/D^0 ratio compared to PYTHIA calculations.
  - Coalescence hadronization;
  - Λ_c contributes sizably to the total charm cross section.



Nucl. Phys. A 982:659-662 (2019)
Ko: Eur. Phys. J. C78:348 (2019)
Greco: Phys. Rev. C 79:044905 (2009)



Λ_c^+ = udc

$c\tau$ = 59.9 μm

$\Lambda_c^+ \rightarrow K^- p \pi^+$ (6.23%)

Explore capability of Λ_c measurement at future sPHENIX experiment!

Particle identification scenarios

1, **No PID**

currently default in the simulation.

2, **clean PID**

at low pT enabled by TOF, no PID at high pT.

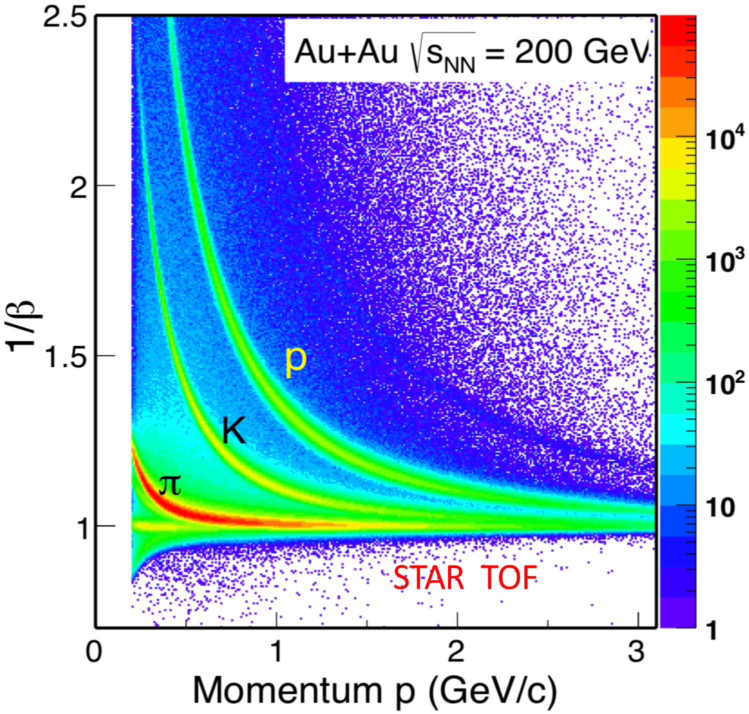
- K/ π separation up to 1.6 GeV/c, protons up to 3 GeV/c;
- TOF matching efficiency (~58%) taken from STAR.

3, **Hybrid PID**

TOF PID if matched to TOF; otherwise no PID.

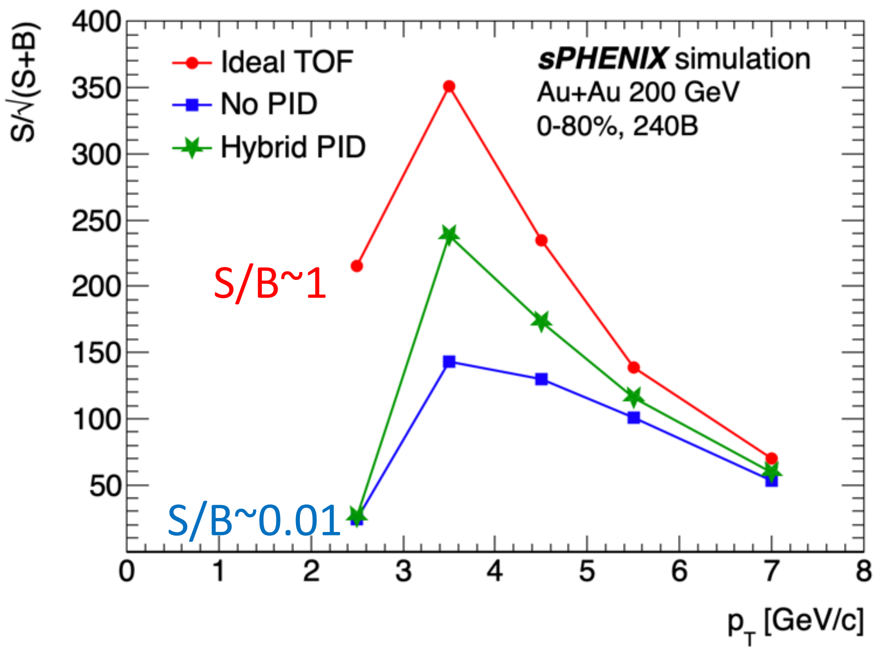
4, **Ideal TOF PID**

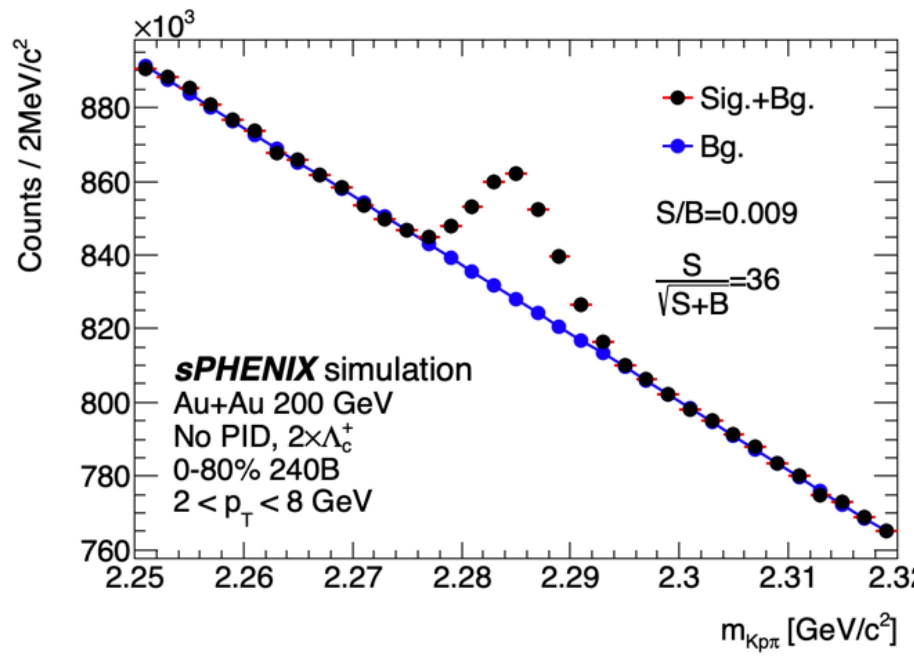
similar as 2, but assuming 100% TOF matching efficiency.



Projected Λ_c significance

240B MB events, $\Lambda_c + \overline{\Lambda_c}$



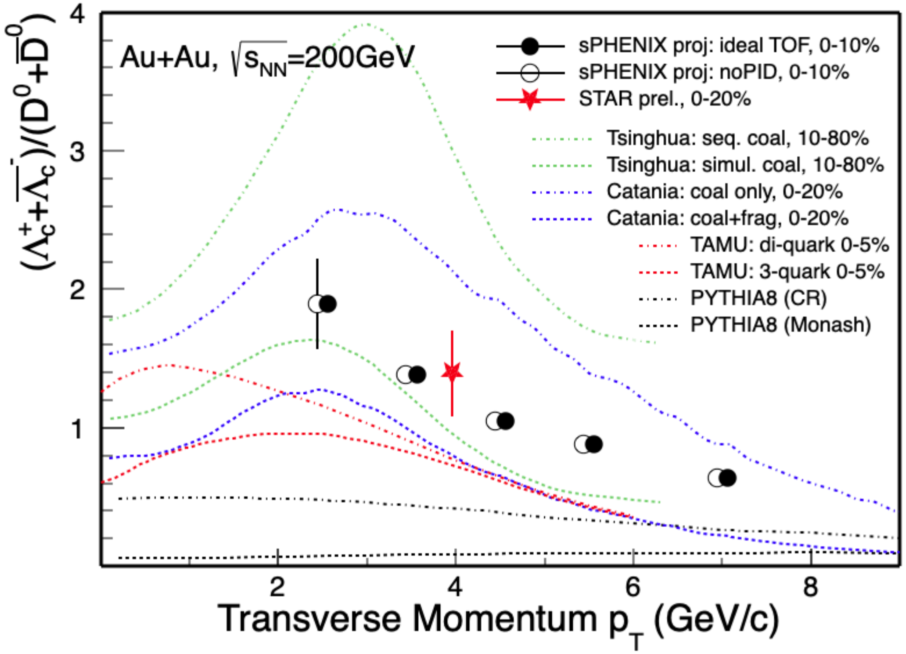


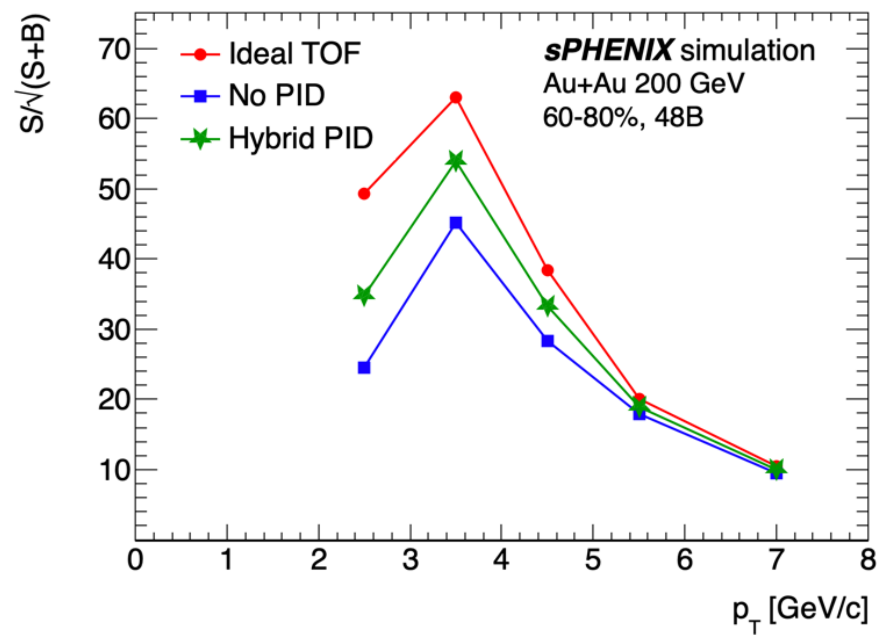
- Precise measurement of Λ_c is expected at sPHENIX at 0-80%;
- PID detector helps suppress the background significantly.

Projected Λ_c significance

Most central collision

Most peripheral collision

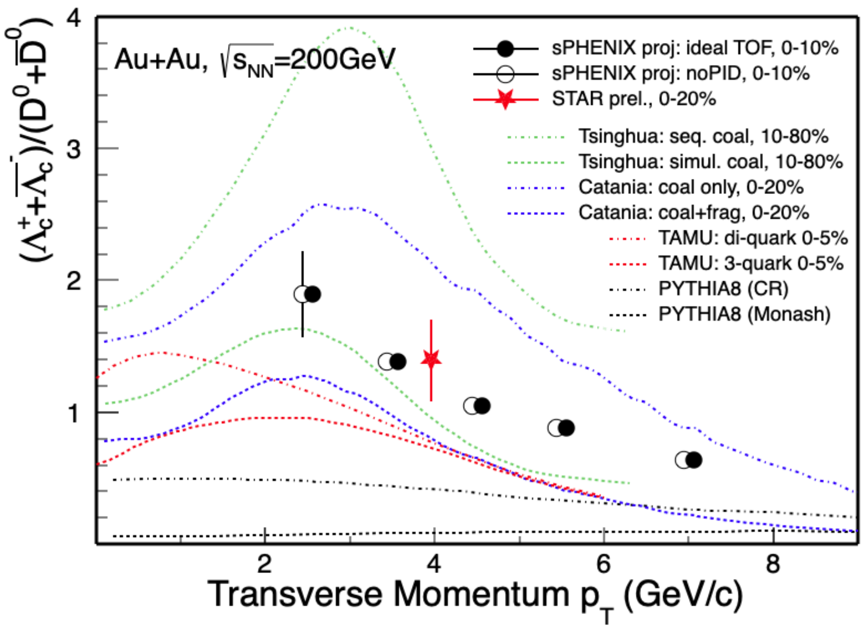


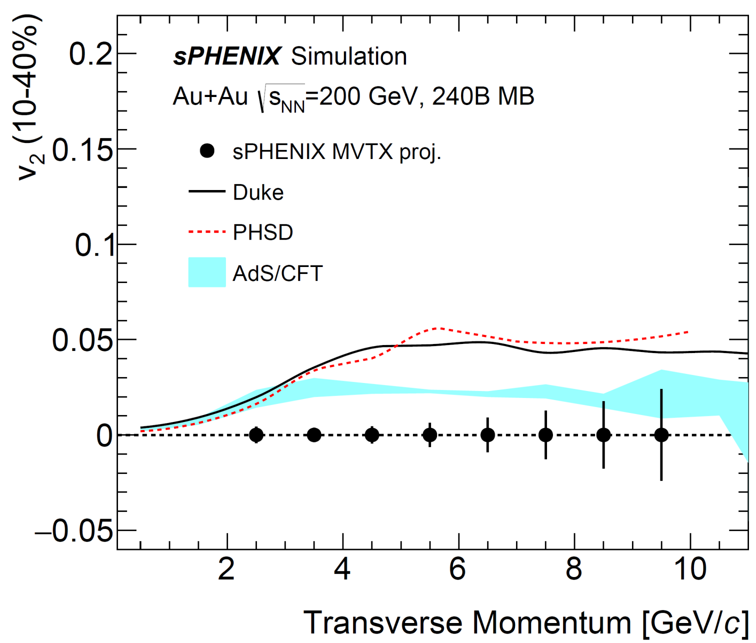


- Very nice performance at $p_T > 3$ GeV in 0-10%;
- Low p_T (< 2 GeV) measurement might need the help from PID detector in 0-10%;
- Enable more precise centrality dependence study.

Summary

- Rich heavy flavor physics opportunity at sPHENIX
  - Upsilon: Color screening length
  - b-jets, B mesons: HF energy loss in QGP, HF diffusion coefficient
  - HF baryons: HF hadronization mechanism
- sPHENIX construction ramping up. First data in 2023
  - Successful PD 2/3 review
  - MVTX electronics and sensor staves production starting soon at CERN



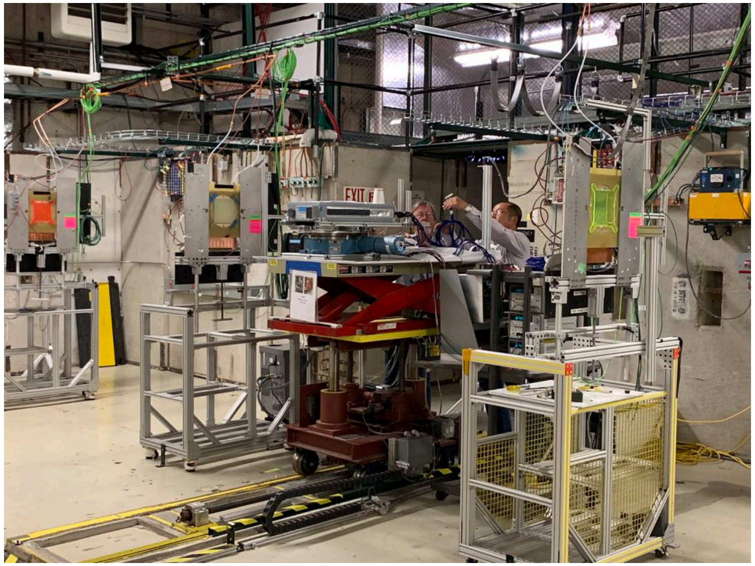


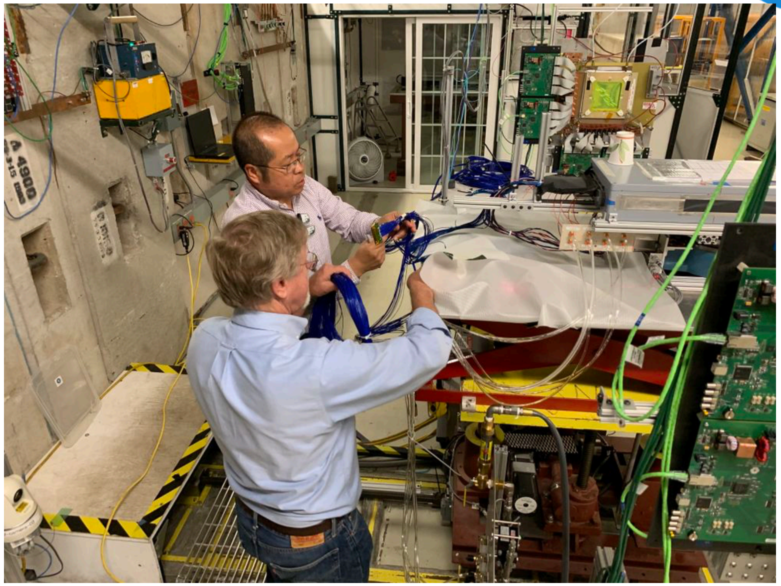
sPHENIX collaboration

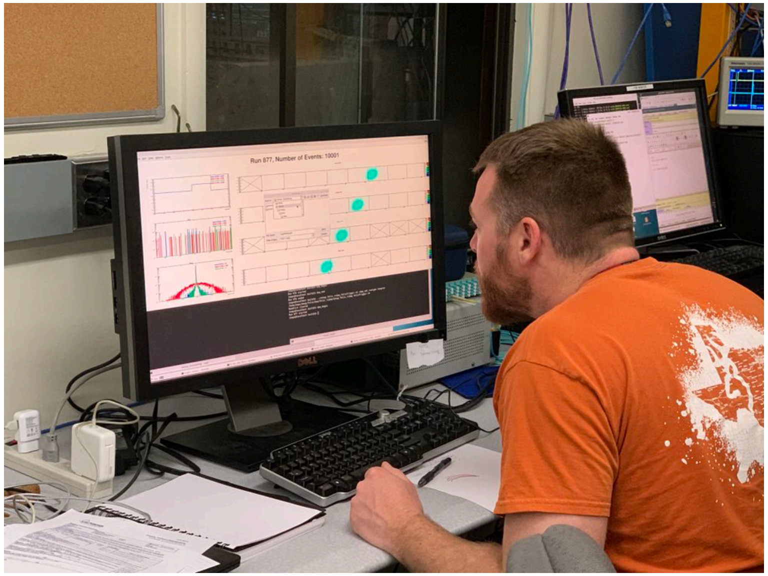
sPHENIX collaboration

- Back up slides

MVTX beam test @ FNAL 2019







Λ_c simulation @ sPHENIX

Input k/π/p

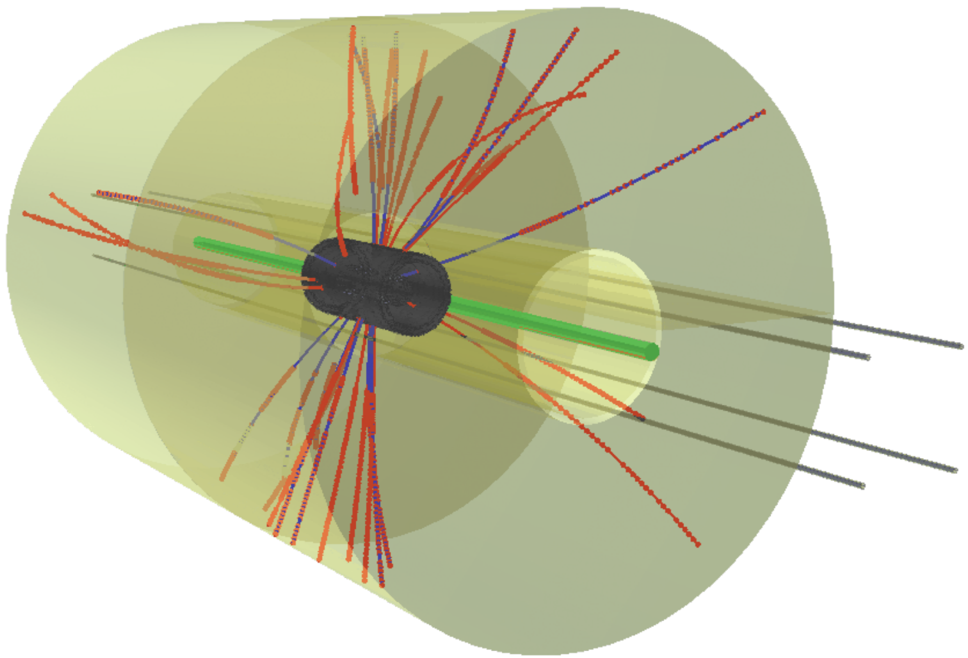
Smear DCA , momentum, add tracking efficiency, (PID)

Apply cuts, reconstruct Lc/Background

Signal:
Decay Λ_c by EventGen;
Λ_c p_T weight: Λ_c /D^0 × D^0 spectra fitted to STAR data.

Combinatorial background
Particles from primary vertex:
Sample the p_T , η, φ of particles
Particles from secondary vertex:
Charm decay K/π/p
Generated by PYTHIA 8

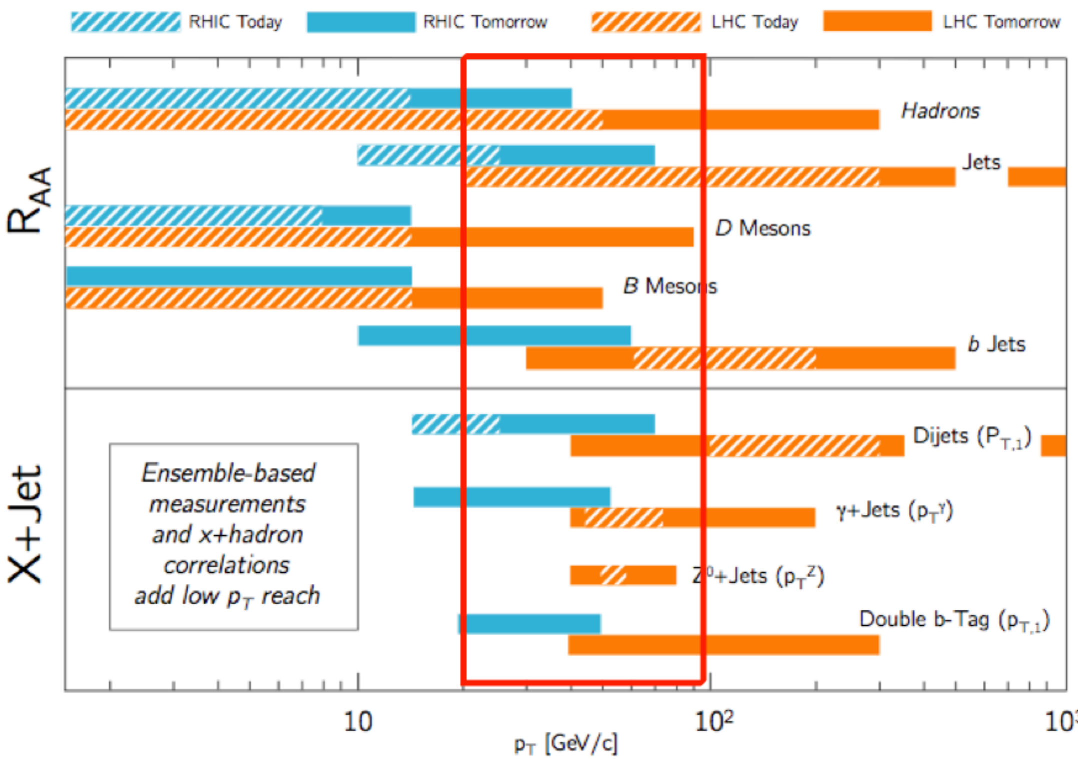
Tracking



p + p, √ s = 200 GeV
di-*b*-jet production at p_T~40 GeV/c

Science mission: Complementarity of RHIC and LHC

High pT @LHC:
Extend kinematic reach vs RHIC
Add new probes



High pT @LHC:
Extend kinematic reach vs RHIC
Add new probes

Overlap in kinematic reach:
Study the same probe for different QGP evolution

5-years run plan

Table 1: Five-year run plan scenario for sPHENIX. The recorded luminosity (Rec. Lum.) and first sampled luminosity (Samp. Lum.) values are for collisions with z-vertex $|z| < 10$ cm. The final column shows the sampled luminosity for all z-vertex values, relevant for calorimeter only measurements.

Year	Species	Energy [GeV]	Phys. Wks	Rec. Lum.	Samp. Lum.	Samp. Lum. All-Z
Year-1	Au+Au	200	16.0	7 nb^{-1}	8.7 nb^{-1}	34 nb^{-1}
Year-2	p+p	200	11.5	—	48 pb^{-1}	267 pb^{-1}
Year-2	p+Au	200	11.5	—	0.33 pb^{-1}	1.46 pb^{-1}
Year-3	Au+Au	200	23.5	14 nb^{-1}	26 nb^{-1}	88 nb^{-1}
Year-4	p+p	200	23.5	—	149 pb^{-1}	783 pb^{-1}
Year-5	Au+Au	200	23.5	14 nb^{-1}	48 nb^{-1}	92 nb^{-1}

Table 2: Summary of integrated samples summed for the entire five-year scenario.

Species	Energy [GeV]	Rec. Lum.	Samp. Lum.	Samp. Lum. All-Z
Au+Au	200	35 nb^{-1} (239 billion)	80 nb^{-1} (550 billion)	214 nb^{-1} (1.5 trillion)
p+p	200	—	197 pb^{-1} (8.3 trillion)	1.0 fb^{-1} (44 trillion)
p+Au	200	—	0.33 pb^{-1} (0.6 trillion)	1.46 pb^{-1} (2.6 trillion)

Upsilon measurement by STAR